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VOLCANIC EARTHQUAKES

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Volcanic earthquakes, according to the late Professor Mercalli, are those which have their centers of maximum intensity under or close to the cones of active or semi-extinct volcanoes.[1] Professor Omori somewhat enlarges this definition. "A volcanic earthquake," he says, "may be defined as a seismic disturbance, which is due to the direct action of the volcanic force, or one whose origin lies under, or in the immediate vicinity of, a volcano, whether active, dormant or extinct."[2] Of the two definitions, the latter is the wider in its scope, for it includes the earthquakes which visit extinct volcanoes, such as the Alban Hills near Rome—earthquakes which differ in no important particular from those of an active volcano like Etna or of a dormant volcano such as M. Epomeo in the island of Ischia.

Mercalli follows up his definition of volcanic earthquakes by describing their important properties. The earthquakes, he says, (1) are felt many times in an area which is very restricted, although the shocks are violent; (2) they precede slightly, but sometimes accompany or follow, the eruptions of the neighboring volcano; and (3) they are repeatedly felt in the same area with similar characters so long as the volcano maintains its activity without notable change. Tectonic earthquakes differ in the following respects from volcanic earthquakes: (1) for the same intensity at the epicenter, they are felt over a much wider area; (2) though they sometimes occur in the immediate neighborhood of active volcanoes, they are as a rule quite independent of volcanic eruptions; and (3) great tectonic earthquakes seldom revisit the same district except at wide intervals of time. It will be seen later that these are not the only important differences between volcanic and tectonic earthquakes. For the present, however, it may be inferred that volcanic earthquakes as a rule originate in shallow foci which are confined to a limited region, while tectonic earthquakes spread from deeply seated foci that are subject to continual change.

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[1] G. Mercalli, *Vulcani e Fenomeni Vulcanici in Italia* (1883), p. 355.

[2] F. Omori, *Bull. Imp. Earthquake Inv. Com.*, Vol. VI (1912), p. 8.

Professor Omori notices that, under his definition, tectonic earthquakes may occasionally be included—earthquakes which disturb large areas[1] and are recorded by seismographs at very distant stations. For instance, about thirty hours before the eruption of the Usu-san (north Japan) on July 25, 1910, an earthquake occurred that was felt to a distance of 87 miles from the volcano and was recorded at a distance of 475 miles.[2] The beginning of the great eruption of the Sakura-jima (south Japan) on January 12, 1914, was followed after a few hours by an earthquake that damaged houses in Kagoshima and the surrounding country and was recorded in European observatories and probably in all parts of the world. Moreover, one month later, on February 13, another strong earthquake took place during an eruption of the Iwo-jima, a volcano belonging to the same chain as the Sakura-jima.[3] To these examples may be added the destructive Hawaiian earthquake of April 2, 1868, which originated in or near the southern part of Hawaii at nearly the same time as great eruptions of

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[1] The occurrence of such earthquakes has long been recognized. For instance, G. P. Scrope, in his *Considerations on Volcanos* (1825), states that "those shocks . . . . which are felt to a considerable distance, are probably caused by new rents produced in the solid subjacent strata supporting or surrounding the mountain, and enter into that class of earthquakes which were discussed in a former chapter," that is, of tectonic earthquakes (p. 155).

[2] F. Omori, *Bull. Imp. Earthquake Inv. Com.*, Vol. V (1911), p. 15; Vol. VI (1912), p. 9.

[3] *Ibid.*, Vol. VIII (1914), p. 23; see also *Nature*, Vol. XCII (1914), pp. 716–17.

Kilauea and Mauna Loa, and was certainly felt in the island of Kauai, about 350 miles from the epicenter, or probably over an area of 375,000 square miles.[1]

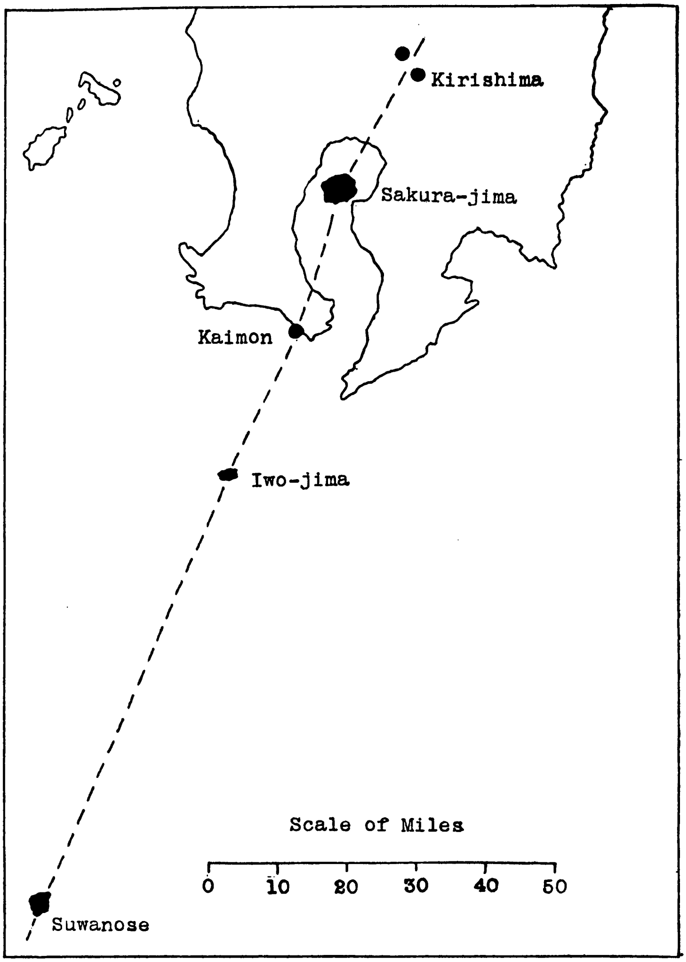

FIG. 1.—Map of volcanic chain in south Japan

It is of some consequence to decide whether such earthquakes should be regarded, as they would be under Professor Omori's definition, as volcanic earthquakes. The course of the volcanic chain of southern Japan referred to in the last paragraph is shown in the accompanying sketch map (Fig. 1), and it is interesting to notice the progressive awakening from north to south of the volcanic foci along its course. On November 18, 1913, the Kirishima-yama broke out in strong eruption, which lasted into the following year. The Sakura-jima followed on January 12, 1914; and, about a month later, the Iwo-jima. When three volcanoes, situated as these are and all of infrequent activity, break into eruption so nearly together, and when two of the eruptions are accompanied by strong and deeply seated earthquakes, it would seem natural to ascribe both phenomena to a common cause—the earthquakes directly, and the eruptions indirectly—to the stress accumulation along the whole volcanic chain.[1]

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[1] See an admirable paper by H. O. Wood, "On the Earthquakes of 1868 in Hawaii," *Bull. Seis. Soc. of America*, Vol. IV (1914), pp. 169-203.

It seems to me, then, that tectonic earthquakes which originate in the immediate neighborhood of volcanoes and even concurrently with eruptions of the same, are not directly of volcanic origin, and should not, by reason of such proximity, be regarded as volcanic earthquakes. I venture, therefore, to suggest that the definitions of such earthquakes given by the two distinguished seismologists referred to should be somewhat modified and should be replaced by the following: A volcanic earthquake is an earthquake directly due to the operations which result or tend to result in a volcanic eruption or is due to relative movements, by whatever cause they may be produced, along fractures of the volcanic mass, whether the volcano itself is active, dormant, or extinct.

Adopting this as the definition of a volcanic earthquake, I propose in the first section of this paper to describe the earthquakes connected with a few typical volcanoes, namely, certain Japanese volcanoes (the Usu-san, the Asama-yama, and the Sakura-jima) and Etna, as examples of active volcanoes, and M. Epomeo in Ischia and the Alban Hills near Rome as examples of dormant and extinct volcanoes respectively. In the second section is given a summary of the characteristic phenomena of volcanic earthquakes; and in the third and last section the modes of origin of volcanic earthquakes will be considered.

[1] F. Omori, *Bull. Imp. Earthquake Inv. Com.*, Vol. VII (1914), pp. 23–24.

I. DESCRIPTION OF SOME VOLCANIC EARTHQUAKES

1. JAPANESE VOLCANOES

Usu-san and Sakura-jima.—The Usu-san is situated near the southwest end of Hokkaido, the northern island of Japan, and the Sakura-jima in the Bay of Kagoshima on the south coast of Kyushu, the southern island. The last eruption of the Usu-san began at 10 P.M. on July 25, 1910, and that of the Sakura-jima at 10 A.M. on January 12, 1914.

Both eruptions were preceded by a large number of earthquakes. Those of the Usu-san outburst began on July 21. At Nishi-Monbets, about 5 miles from the center of the volcano, 25 shocks were felt on July 22, 110 on July 23, 351 on July 24, and 165 on July 25. Once the eruption had begun, the seismic frequency decreased. At Sapporo, about 44 miles from the volcano, the earthquakes were registered by a horizontal pendulum seismograph, the numbers being 1 (at 4:18 P.M.) on July 21, 3 on July 22, 23 on July 23, 76 on July 24, 84 on July 25; after the eruption there was a rapid decline in frequency, the numbers being 26 on July 26, 15 on July 27, 5 on July 28, 6 on July 29, and 1 on July 30. The eruption continued until the end of the year.[1]

At Kagoshima, which is about 6 miles from the center of the Sakura-jima, the first earthquake was felt at 3:41 A.M. on January 11, 1914. At the Kagoshima Observatory the earthquakes were recorded by a Gray-Milne seismograph, the average hourly frequency being 4.1 from 3 to 11 A.M. on January 11, 12.4 from 11 A.M. to 8 P.M., and 19.5 from 8 P.M. on January 11 to 10 A.M. on January 12. The greatest hourly numbers were 28 at 8–9 P.M. on January 11 and 27 at 3–4 A.M. on January 12. The total number of shocks registered from 3 A.M. on January 11 to 10 A.M. on January 12 was 418. After the first eruption at the last-mentioned hour, there was a marked decline in earthquake frequency, the numbers being: 10–11 A.M., 17; 11–noon, 11; noon–1 P.M., 6; 1–2 P.M., 3; 2–3 P.M., 5; 3–4 P.M., 2; 4–5 P.M., 2; 5–6 P.M., 2. At 6:30 P.M., the seismograph was injured by the strong tectonic earthquake referred to above.[2]

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[1] *Ibid.*, Vol. V (1911), pp. 8–17.

[2] *Ibid.*, Vol. VIII (1914), pp. 9–14, 22–27.

Thus, both eruptions were preceded by a marked increase in seismic frequency, followed by a marked decrease, the maxima occurring 24 hours before the first outburst of the Usu-san and about 13 and 6 hours before that of the Sakura-jima.[1]

Observations were made with a portable horizontal tromometer erected by Professor Omori at Nishi-Monbets (5 miles from the Usu-san) from July 30 to August 6, and at the West-Kohan School (Sobets) at the foot of the East Maru-yama from August 6 to 10. At this place, which is close to the nearest craterlet, series of well-defined, small, quick, unfelt vibrations, called micro-tremors by Professor Omori, were registered, which were entirely absent from the records at Nishi-Monbets. The mean range of motion was in every case less than one-tenth of a millimeter; but the principal periods of the tremors (.53, 1.08, 1.59, 2.14 seconds) were practically identical with those of earthquake vibrations recorded at Nishi-Monbets (.53, 1.01, 1.58, 2.43 seconds). It would seem, then, that the micro-tremors are in reality true earthquake vibrations, but so weak that they cannot be recorded more than a few miles from the origin. Professor Omori notices that the shortest of the foregoing periods is approximately one-half, one-third, and one-quarter of the other periods. He also shows that moderate explosions from even the nearest craterlet were not as a rule accompanied by marked micro-tremors; whereas violent explosions from that and other craterlets were usually accompanied, and often preceded by several minutes, by well-pronounced micro-tremors. The tremors, however, were not confined to the epochs of explosions. They sometimes occurred when the smoke ejections from the different craterlets were insignificant and even when they had completely ceased. At such times, as Professor Omori suggests, eruptions were perhaps prevented by the temporary stoppage of the craterlets.[2]

Asama-yama.—The Asama-yama, one of the greatest of Japanese volcanoes, rises from the plateau of the central island of

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[1] Professor Omori's observations give precision to a fact which has long been known. "It is," says G. P. Scrope in his *Considerations on Volcanos* (1825), "a remark common to the observations made on almost all volcanic eruptions, that local earthquakes always precede the emission of lava currents, and cease while the lava is flowing, to recommence when it has stopped" (p. 155).

[2] *Op. cit.*, Vol. V (1911), pp. 31–38.

Japan to a height of 8,140 feet above the sea. After a prolonged period of rest, it has been subject for about six years to a series of strong explosions, the first of which occurred on February 13, 1908.

Observations with horizontal pendulum seismographs were instituted by Professor Omori at two stations on the southwest flank of the volcano, Yuno-taira and Ashino-taira, at heights of 6,306 and 4,422 feet above the sea. Owing to weather conditions, the observations at the former station were confined to the summer months.

The seismograms obtained at these places showed that there were two distinct types of earthquakes, some being independent of any outburst of the volcano, while others were invariably the results of explosions.

The two types of earthquakes are characterized by several marked differences, of which the following are the more important:

a) The shocks without explosions consisted only of minute quick vibrations, while those with explosions consisted of slow movements (of as much as 2.6 and 5.3 seconds' period), on which after a few seconds quick vibrations were superposed.

b) The earthquakes without explosions were distinctly stronger than the others, probably because, as Professor Omori suggests, a great part of the energy of the explosions is expended in the projection of rock fragments and débris. Of 1,485 earthquakes without explosions, 21 per cent were sensible at Yuno-taira; of 8,847 earthquakes with explosions, only 0.3 per cent were sensible. Moreover, the strong earthquake of May 26, 1908, which did not accompany an explosion and which evidently originated in the volcano itself, was felt over an area of 2,400 square miles.[1]

c) The earthquakes without explosions were of shorter duration than those with explosions, the averages for the former being 16.7 seconds in 1911 and 15.0 seconds in 1912, and for the latter 33.2 seconds in 1911 and 32.7 seconds in 1912.

d) The two types of earthquakes alternate in frequency. During the two years, 1911–12, the maxima of the earthquakes without explosions occurred at 3–4 A.M., 8–9 A.M., 1–2 P.M., and 8–9 P.M., while the minima of the earthquakes with explosions occurred at 3–4 A.M., 8–9 A.M., 2–3 P.M., and 9–10 P.M. The minima of the former occurred at 6–7 A.M., 11–12 A.M., 6–7 P.M., and 11–12 P.M., while the maxima of the latter occurred at 5–6 A.M., noon–1 P.M., 4–5 P.M., and 1–2 A.M. In August, 1911, the earthquakes with eruptions attained their maximum frequency (205) for the year, and the earthquakes without eruptions their minimum frequency (38); in October, 1912, there was a maximum of earthquakes with eruptions (626) and a minimum of earthquakes without eruptions (10). A similar relation is shown in the variation of frequency from one year to another, as will be seen in the following table:[1]

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[1] It may be added that the Usu-san explosions of 1910 were preceded by many sensible earthquakes, a few of them strong; but, as a rule, they were unaccompanied by sensible shocks.

	EARTHQUAKES WITHOUT ERUPTIONS			EARTHQUAKES WITH ERUPTIONS		
	Sensible	Unfelt	Total	Strong Explosions	Small Outbursts	Total
1911........	57	321	378	0	577	577
1912........	124	563	687	0	1111	1111
1913........	6	28	34	25	7101	7126
1914........	11	37	48	1	30	31
1915........	44	65	109	0	0	0
1916........	64	165	229	0	2	2

2. ETNA

Etna rises from a nearly circular base, measuring 428 square miles, to a height of 10,870 feet. Earthquakes occur on all sides of the mountain, and, for many years past, they have been especially frequent beneath its southeastern flank. In the present section, I propose to describe a few typical earthquakes on this flank, and to refer very briefly to the distribution of the epicenters within the area covered by the volcano.

The earthquakes belong as a rule to one of two classes, according as the greater axes of their meizoseismal areas are directed nearly along or perpendicular to the radii from the central crater. They may therefore be called *radial* and *perimetric* earthquakes, respectively.

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[1] After May 5, 1914, there was no strong outburst of the Asama-yama.

As examples of radial earthquakes on the southeastern flank, I have selected three which have been studied in perhaps greater detail than others, namely, the Fondo Macchia earthquake of July 19, 1865, the Fleri earthquake of August 8, 1894, and the Linera earthquake of May 8, 1914. The Fondo Macchia earthquake of October 15, 1911, is given as an example of a perimetric earthquake.

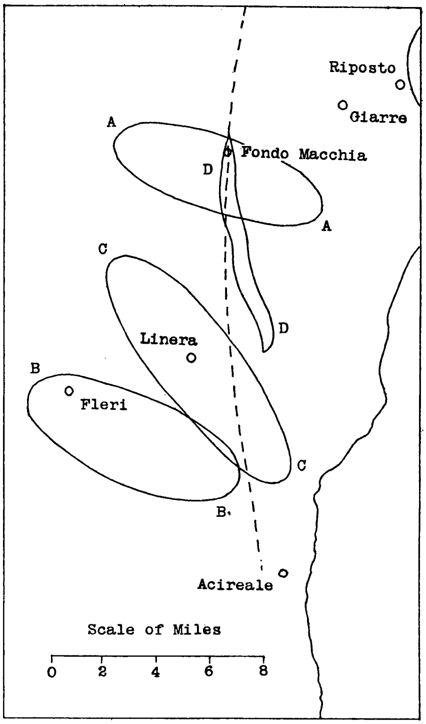

FIG. 2.—Map of earthquakes on southeast flank of Etna.

Radial earthquakes.—On January 30, 1865, a great eruption took place on the east-northeast flank of Etna, which lasted nearly twelve weeks. Eighty-eight days after its close, on July 19, Fondo Macchia was completely destroyed by an earthquake, and the neighboring villages of Baglio, Rondinello, Scaronazzi, and S. Venerina were seriously damaged, though not ruined. The meizoseismal area was a narrow band directed W.NW. and E.SE., a little over 4 miles in length and about $\frac{2}{3}$ mile wide. Outside this band, the shock was disastrous within an area 5 miles long and $1\frac{1}{4}$ miles wide, represented by the curve *A* on the sketch map (Fig. 2). The intensity of the shock diminished rapidly toward the north, and more slowly toward the south, but at no place more than 12 miles from the epicenter was the shock felt. The area disturbed cannot therefore have exceeded 113, and was probably less than 100, square miles. A number of after-shocks followed this earthquake, 24 being felt in July (3 of them very strong at

Fondo Macchia), and several others, more or less slight, in the following month, the series ending on August 23.[1]

The earthquake of August 8, 1894, differed in two respects from many Etnean earthquakes. It occurred while the volcano was in a state of only moderate activity, and it disturbed an area unusually large for the district, although small for a shock of such intensity. It was preceded by a violent shock at 1:58 P.M. on August 7, strongest at Fleri, Zerbate, etc., and felt generally at Catania and Zafferana, and by a few persons at Nicolosi and Trecastagni. Three other shocks followed in the meizoseismal area before the occurrence of the principal shock of the series at 6:16 A.M. on August 8. By this shock, the villages of Fleri, Pisano, Zerbate, etc., were ruined. The meizoseismal area, about 4 miles long from northwest to southeast and 2 miles wide, is represented by the curve *B* in Figure 2. From this area, the intensity of the shock diminished outward rather, but not very, rapidly, the disturbed area including the whole base of Etna and probably on the whole as much as 800 square miles. Within or near the epicentral district, at least 15 after-shocks were felt before the end of the month.[2]

Few, if any, Etnean earthquakes have thrown so much light on the nature and origin of volcanic earthquakes as the remarkable series which culminated in the Linera earthquake of May 8, 1914. They have been studied by Professor G. Platania in one of the most valuable memoirs that we possess on volcanic earthquakes.[3] In all respects except in the shallowness of the foci, they resemble true tectonic earthquakes. They were preceded and followed by long series of accessory shocks, and, along the axis of the meizoseismal area, there were displacements of a pre-existing fault.

Omitting instrumental shocks, the whole series contained 55 earthquakes, 21 being fore-shocks from April 28 to May 7, and 33 after-shocks from May 8 to June 4. Five of the fore-shocks and seven of the after-shocks were strong. The broken line on the map (Fig. 3) includes all the places in which houses were damaged by the different shocks of the series. The smaller curves represent the meizoseismal areas of the more important shocks. Thus, the curves 1 and 2 indicate the meizoseismal areas of the double earthquake of May 7 at 6:35 P.M., houses being damaged at Piano d'Api (No. 1) and at Pennisi and Fiandaca (No. 2). At 10 P.M. on the same day, another strong earthquake caused damage at Fossalacqua (No. 3) along a fracture which may be a continuation of that at Fiandaca (No. 2). The principal earthquake occurred at 7:2 P.M. on May 8, and was ruinous within the area bounded by the ellipse (No. 4), the zone of complete ruin being much less wide. With this earthquake also there was a zone of serious damage to houses at Dagala (No. 5), separated from the principal zone by a wide tract of little or no damage to property. Lastly, the curve No. 6 shows the boundary of slight damage near Viagrande wrought by the after-shock of May 26.

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[1] A. Riccò, *Boll. Soc. Sism. Ital.*, Vol. XVI (1912), pp. 27–31; M. Baratta, *Boll. Soc. Geogr. Ital.* (1894), pp. 12–13, and *I Terremoti d'Italia*, pp. 442–43.

[2] M. Baratta, *Boll. Soc. Geogr. Ital.* (1894), pp. 6–9, 23.

[3] "Sul periodo sismico del maggio 1914 nella regione orientale dell'Etna," *Pubbl. dell'Ist. di Geogr. Fis. e Vulcan. della R. Univ. di Catania*, No. 5, 1915.

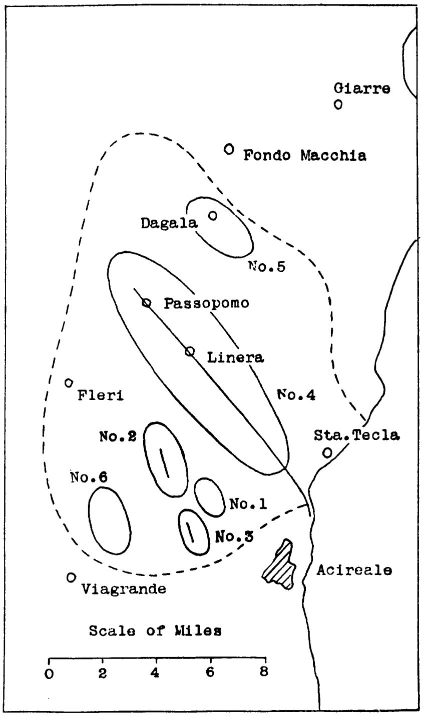

FIG. 3.—Map of Linera earthquakes of 1914

The meizoseismal area of the principal earthquake (bounded by the curve *C* in Fig. 2 and No. 4 in Fig. 3), within which the ruin was practically complete, is very elongated, being about 4¼ miles long, with a maximum width near Linera of 1¼ miles. In this zone, not only are the houses completely razed to the ground, but the ground itself is crushed. Along the axis of this zone, there runs a slightly sinuous fracture with, in parts, a secondary nearly parallel fracture separated by a distance of from 2 to 50 or more yards. The most destructive effects of the earthquake are concentrated along this fracture, starting from Passopomo, through Linera, to beyond Mortara. Here the railway line was seriously damaged, the rails being displaced and contorted. The fracture can be followed as far as the seacoast, bending slightly to the south in the neighborhood of Sta. Tecla. Almost throughout the fractured zone there is a change of level, in some places of only an inch or two in others of 15 or 16 inches, and in one, near the seacoast, of more than 3 feet, the ground of the southwest side being left at a higher level than that on the northwest side.[1] The fracture is by no means a recent one, for it has been known since 1879, and Professor Platania states that displacements have occurred along it in previous earthquakes. Nor is it the only fracture along which movements have taken place during this series of earthquakes. There is a second at Fiandaca (No. 2), which was observed during the earthquakes of 1894 and 1907, and which probably corresponds with another at Fossalacqua (No. 3). Near this fracture occurred the greatest damage wrought by the two strong fore-shocks of May 7.

During the interval covered by this series of earthquakes there was a marked increase in the activity of Etna, though the different shocks were not coincident with the volcanic explosions.

Perimetric earthquakes.—On September 10, 1911, a great eruption of Etna began, and, notwithstanding the extraordinary energy of the early phenomena, ceased after only thirteen days of activity. Three weeks later occurred the destructive Fondo Macchia earthquake of October 15, 1911. This earthquake was, however, preceded by at least 10 fore-shocks, the first 5 of which occurred on September 30 at Pisano (intensity 7, Mercalli scale), October 9 (2 shocks) at Piano d'Api (intensity 5), and October 14 at S. Venerina (intensity 6). The principal shock (intensity 10) occurred at 9:52 A.M. on October 15, and was followed by 4 slight after-shocks on October 24 and 1 on November 9.

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[1] There is also some evidence of horizontal displacement. A high wall in the upper part of the fractured zone is curved and shifted toward the southeast.

The isoseismal lines of intensities 10, 8, 6, 4, and 2 (Mercalli scale) are shown in Figure 4, the line of intensity 10 being also represented by the curve *D* in Figure 2. The meizoseismal area (bounded by the isoseismal 8) is a slightly sinuous band, running from N.NW. to S.SE., 4 miles long, about $\frac{1}{3}$ mile wide, and $1\frac{1}{4}$ square miles in area. Within it is a band, including Fondo Macchia, in which the destruction of buildings was complete, this band being about 3 miles long and $\frac{1}{4}$ mile wide. Notwithstanding the great intensity within this band, the shock was not felt at places 6 miles to the west, the area within the isoseismal 4 contained not more than about 70 square miles, and the whole district shaken only about 230 square miles. The mean duration of the shock was about 8 seconds.

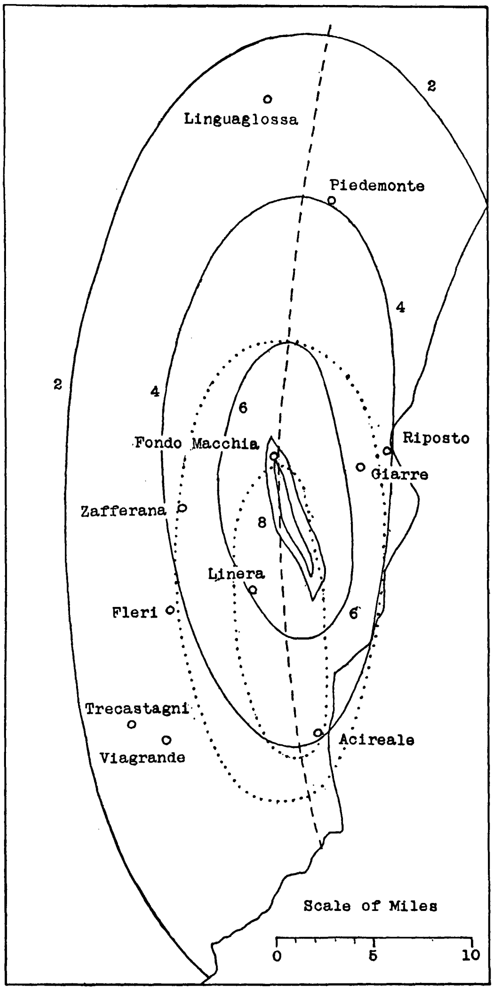

Fig. 4.—Map of Fondo Macchia earthquake of October 15, 1911.

During the eighteen years (1893–1911) preceding this earthquake, 27 shocks more or less strong originated within the elliptical area represented by the outer dotted line in Figure 4. Six of these earthquakes were of ruinous strength, with their epicenters at Fondo Macchi, Zerbate, S. Leonardello, and Aci Platania, all included within the area represented by the smaller dotted ellipse in Figure 4. The two ellipses have their longer axes coinciding with those of the isoseismal lines of the Fondo Macchia earthquake of 1911. Close to these axes and nearly parallel to them, runs a fault known as the *Timpa della Scala* and represented by the broken line on the map. The western limb at the south end has undergone, and is still undergoing, elevation; while the eastern limb at the north end is subsiding.[1]

Distribution of Etnean earthquakes.—A few of the Etnean earthquakes disturb the whole area of the volcano; but the majority are strongly felt in one or a few of the villages scattered over the mountain sides. In such cases the villages affected cannot be far distant from the epicentral areas, and Dr. M. Baratta, in his great history of Italian earthquakes,[2] has thus found it possible to distinguish the principal seismic zones of this volcanic region. These are twelve in number, the places which give their names to the different zones being shown in Figure 5, in which the dotted line marks out the base of the volcano: (1) Linguaglossa, to the NE.; (2) Randazzo, to the N.; (3) Adernò-Bronte-Maletto, to the W.; (4) Santa Maria di Licodia, to the S.W.; (5) Paternò, to the S.SW.; (6) Belpasso, to the S.; (7) Nicolosi, to the S.; (8) Trecastagni, to the S. SE.; (9) Acireale, to the SE.; (10) Zafferana-Pisano-S. Venerina, to the E.SE.; (11) Macchia Region, to the E.; and (12) Giarre-Riposto, to the E.

Of these zones, the most important at present are those of Santa Maria di Licodia, Nicolosi, Trecastagni, Acireale, Zafferana-Pisano-S. Venerina, and the Macchia Region. The Fleri earthquake of 1894, described above, is included in the Acireale zone, the Linera earthquake of 1914 in the Zafferana zone, and the Fondo Macchia earthquakes of 1865 and 1911 in the Macchia zone. The Nicolosi zone gives rise to many and violent earthquakes, and it is remarkable that some of the greatest are quite local. For instance, the earthquake of May 11, 1901, damaged many houses in Nicolosi (intensity 8), and yet was only just perceptible at a distance of 3 or 4 miles.[1] The earthquake of May 14, 1898, is typical of the S. Maria di Licodia zone; nearly all the houses in S. Maria di Licodia were damaged, and slight injury occurred in other villages on the southwest slope from Belpasso to Adernò, the shock being thus rather more widely felt than the Nicolosi earthquake.[2]

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[1] A. Riccò, *Boll. Soc. Sis. Ital.*, Vol. XIX (1912), pp. 9-38.

[2] *I Terremoti d'Italia*, pp. 829-33.

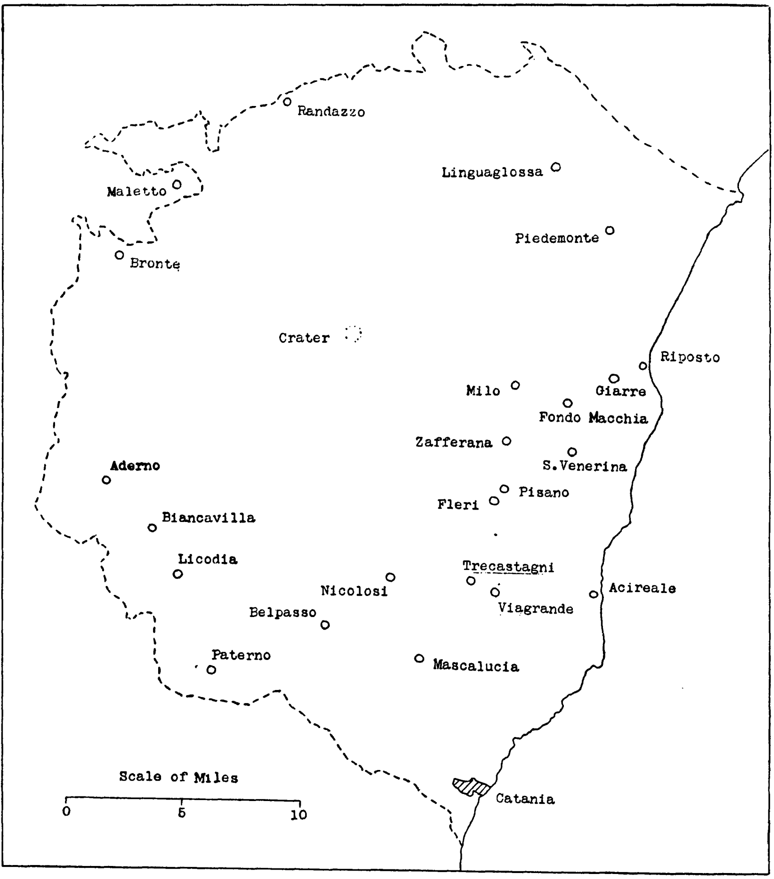

FIG. 5.—Map of Etna and seismic districts

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[1] S. Arcidiacono, *Boll. dell' Accad. Gioenia di Sci. Nat. in Catania*, Fasc. 70 (1901).

[2] A. Riccò, *op. cit.*, Fasc. 53-54 (1898).

For many years past the most active zones have been those between the eastern and southern radii. But the seismic foci migrate from one zone to another without (at present) any apparent law. Take, for instance, the earthquakes of one year only, the year 1903.[1] On January 30 there was a shock of intensity 5 at Giarre, Zafferana, Milo, Viagrande, Linguaglossa, and Randazzo (the epicenter being perhaps in zone 12); on March 8, one of intensity 4 between Nicolosi and Mascalucia, but hardly felt at either of these places although they are only 4 miles apart (zone 7); on March 11, one of the same intensity at S. Venerina (zone 10); on March 24, a very slight shock at Belpasso (zone 6); on April 3, a shock of intensity 5, and on April 4 and 5 very slight shocks at S. Venerina (zone 10); on April 7, a shock of intensity 5 at Linguaglossa and Milo (zone 1); on April 13, one of intensity 4 at Biancavilla (zone 4?); on April 19, a slight shock at Paternò (zone 5); on May 26, a very strong shock with slight damage at Trecastagni (zone 8), and only feebly felt at Viagrande, less than a mile away; on June 1, 14 shocks (2 of them of intensity 6) at Pedara and Viagrande; on June 3, 3 shocks at Viagrande; on June 5, 1 shock, and on June 7, 2 shocks, at Trecastagni and Viagrande; on June 11, a slight shock at Trecastagni; and on June 16, 2 very slight shocks at Viagrande (all 23 shocks in zone 8); on July 21, a very slight shock at Belpasso (zone 6); on July 30, a sensible shock at Biancavilla (zone 4?); on August 6, 4 shocks of intensity 4 at Nicolosi, Trecastagni, Zafferana, Milo, and Biancavilla (zone 7?); and, lastly, on November 20, a strong earthquake of intensity 6 at Viagrande, Zafferana, Milo, S. Venerina, Acireale, and Linguaglossa (zone 10). Thus, seven out of the twelve Etnean zones were probably in action in this one year.

3. MONTE EPOMEO (ISCHIA)

The island of Ischia, 6 miles long from east to west and 5 miles in width, is separated from the Italian coast by a distance of only 6 miles. A large part of the island is occupied by the old crater of Monte Epomeo, a volcano which must be regarded as dormant rather than extinct, for the last eruption occurred in

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[1] S. Arcidiacono, *Bull. dell' Accad. Gioenia di Sci. Nat. in Catania*, Fasc. 79 (1903).

1302, and the one before that a thousand years earlier. These eruptions, as well as their more recent predecessors, took place from new vents chiefly on its eastern and northeastern flanks. All of them began suddenly, were accompanied by violent earthquakes, and were preceded by long intervals of repose.

Such an interval, one of more than four centuries, followed the last eruption, and during that time there were no earthquakes of any consequence in the island. Then, during one night—July 28–29, 1762—as many as 62 earthquakes were felt at Casamicciola, some of them strong enough to damage buildings. On March 18, 1796, a severe earthquake occurred, which caused destruction of buildings in Casamicciola alone; on February 2, 1828, one still stronger, which again wrought destruction in that town; others of less consequence, but still strong, occurred on March 6, 1841, and August 15–16, 1867; the last of all being the destructive earthquakes of March 4, 1881, and July 28, 1883.

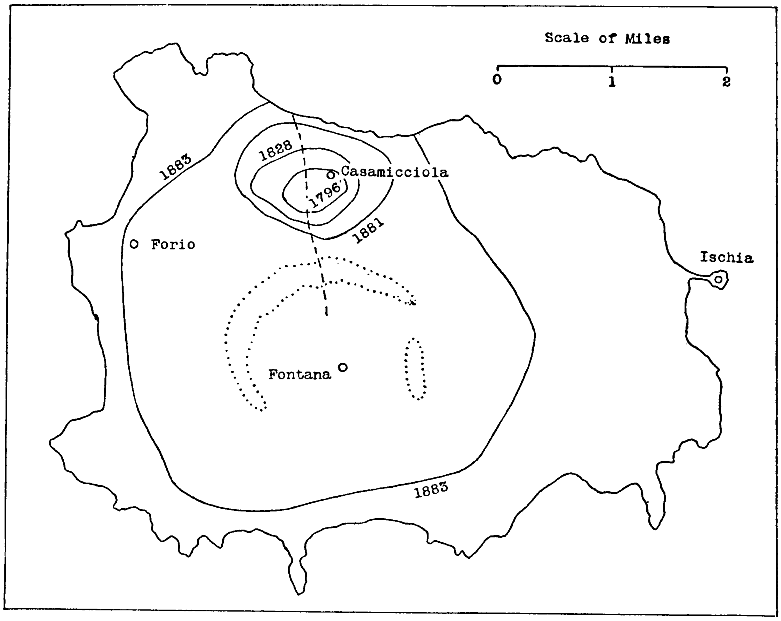

Fig. 6.—Map of Ischian earthquakes

In the accompanying map (Fig. 6) the dotted lines represent the boundaries of those portions of the central crater of Epomeo which are still standing, and the continuous lines the boundaries of the areas within which buildings suffered marked damage by the earthquakes of 1796, 1828, 1881, and 1883. It will be noticed that these areas show a progressive increase in size. The broken line, slightly curved, shows the position of the radial fracture with which the earthquakes were probably connected; and it is important to notice that the chief damage wrought by the earthquakes of 1881 and 1883 was concentrated along this line near Casamicciola.

These earthquakes were studied in great detail by the late Dr. H. J. Johnston-Lavis. The isoseismal bounding the area of complete destruction in 1881 includes only ½ square mile, the area of partial though serious destruction about 2 square miles, and that within which buildings were slightly damaged about 5 square miles. Still farther, the shock continued to diminish rapidly in intensity. It was felt in the neighboring island of Procida, and by some persons, though very slightly, on the Italian coast, the total area being probably less than 300 square miles. From the inclination of the fissures made in buildings, Dr. Johnston-Lavis estimated the mean depth of the focus at about ⅓ mile. The earthquake was followed by a few slight after-shocks on March 7 (2 shocks), 11–12, 15–16, 17–18, and 27(?), April 5 and 6, and July 18.

The earthquake of July 28, 1883, was much stronger, and resulted in great loss of life at Casamicciola. It was preceded at that place by a slight shock on July 24, and by an earth-sound a quarter of an hour beforehand. The areas of complete, partial destruction and slight damage were respectively 3, 11, and 30 square miles. In this earthquake, also, the intensity diminished very rapidly outward. The shock was felt in Italy near the coast and by a few persons in Naples, which is 20 miles from Casamicciola. The disturbed area can hardly therefore have contained more than 1,250 square miles. The mean depth of the focus was again found to be about ⅓ mile. The shock was remarkable for the entire absence of preliminary sound or tremor and for its great initial strength, a great part of the ruin being caused during the first few seconds. Between July 28 and August 3, 21 slight after-shocks were felt in Casamicciola. This, however, was not the only center in action, for several were recorded at the town of Ischia only.[1]

4. ALBAN HILLS

About 15 miles to the southeast of Rome lies a group of extinct volcanoes containing several circular lakes which evidently occupy old craters of the system. The principal hill, Monte Cavo, of which the other and smaller hills may be regarded as lateral cones, rises to a height of nearly 3,000 feet. There is no certain evidence of activity during historic times.

The earthquakes of this district are less frequent and destructive than those of the much larger Etnean region, but in other respects they resemble them closely, and especially in the constant migration of activity from one part of the volcano to another.

One of the most recent in the district is that of February 21, 1906. It was preceded by six very slight fore-shocks, one on February 20, at Ariccia, the others on February 21, at Albano. The principal shock occurred at 9:49 P.M. on February 21, and, from that time until February 23, there were 6 very slight after-shocks. The isoseismal lines of the principal earthquake, which was of intensity 5–6 (Mercalli scale), are represented approximately in Figure 7. They are rather close together, indicating a rapid decline in the intensity of the shock from the epicenter, though a decline less rapid than in other earthquakes of the same district or of the Etnean region. The mean duration of the shock was nearly 4 seconds.[2]

Dr. M. Baratta defines the following seismic zones among the Alban Hills (Fig. 7): (1) Colonna; (2) Montecompatri; (3) Monte Porzio; (4) Frascati; (5) Rocca di Papa-Monte Cavo; (6) Albano; (7) Ariccia; (8) Nemi; and (9) Velletri.[3] To these districts should perhaps be added: (10) Genzano-Civitalavinia.

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[1] G. Mercalli, *L'isola d'Ischia ed il terremoto del 28 luglio 1883* (Milan, 1884); H. J. Johnston-Lavis, *Monograph of the Earthquakes of Ischia* (1885). A summary of these and other memoirs on the Ischian earthquakes is given in my *Study of Recent Earthquakes*, pp. 45–73.

[2] G. Agamennone, *Boll. Soc. Sis. Ital.*, Vol. XXI (1918), pp. 47–101.

[3] *Terremoti d'Italia*, pp. 778–80.

Of these zones, Nos. 1–4 lie on the northern half, and Nos. 6–10 on the southern half, of the volcano.

As in the Etnean region, there is at present no apparent law in the transference of the epicenters from one zone to another. The nature of that transference may be shown by a brief reference to the more important earthquakes of the last forty years. On September 2, 1883, an earthquake of intensity 7 (Mercalli scale) caused slight damage at Frascati, Grottaferrata, Rocca di Papa, and Monte Cavo (zone 4), the axis of the area of maximum intensity being directed southeast or along a radius from the summit of Monte Cavo; on January 17, 1886, there was a very strong shock at Ariccia (zone 7); on January 22, 1892, a shock with its epicenter between Genzano and Civitalavinia (zone 10); on May 8, 1897, a strong shock without damage at Colonna, the axis of the area of maximum intensity being directed southwest or along a radius (zone 1); on November 6, 1897, a shock at Civitalavinia

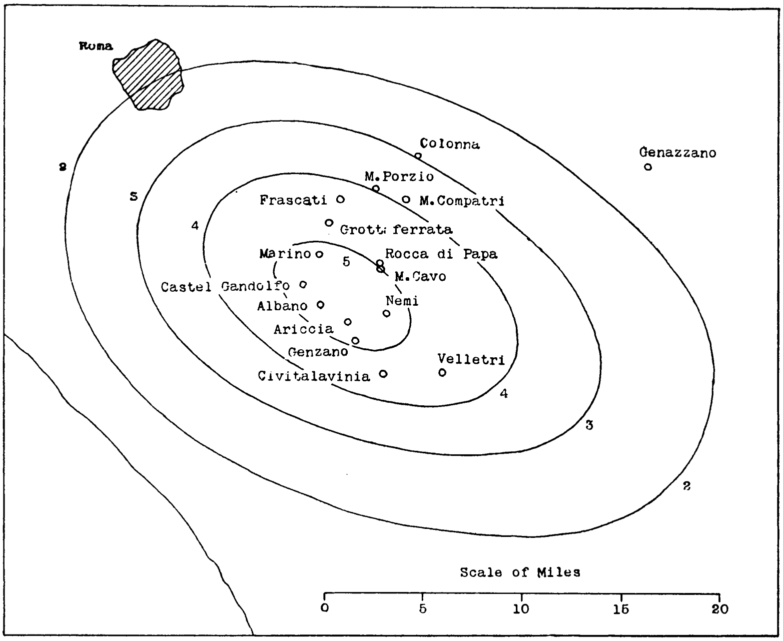

FIG. 7.—Map of Albano earthquake of February 21, 1906

(zone 10), followed a week later (on November 13) by one with its epicenter near Velletri (zone 9); on July 19, 1899, the strongest shock of the series (intensity 8), causing some damage at Frascati (zone 4) and rather less at Marino, the mean duration of the shock 3½ seconds, registered at Lubiano (298 miles to the north) and Catania (318 miles to the south); on October 12, 1902, a shock of intensity 6 at Genzano (zone 10); on February 21, 1906, one of intensity 5–6 at Albano (zone 6); and, lastly, on October 6, 1909, a shock at Frascati (zone 4). Thus, of these ten earthquakes, four originated on the north side, and six on the south side, of the volcano; while six of the ten seismic zones were in action.

II. CHARACTERISTICS OF VOLCANIC EARTHQUAKES

a) While volcanic earthquakes often occur in close connection with eruptions—either shortly before, during, or shortly after them—they seldom coincide with an outburst, except in the case of the weak tremors with which the Japanese records have made us familiar. Nor do the almost contemporaneous earthquakes and eruptions always occur in the same part of the volcano. The Fondo Macchia earthquakes of 1865 and 1911 were felt in a district to the east of the central crater of Etna, while they followed closely on eruptions from the northeastern flank. Some earthquakes, again, occur in active volcanic regions without the accompaniment of any change in volcanic activity; others in regions in which the volcanoes have been extinct for many centuries.

b) In volcanic earthquakes the intensity of the shock is often great near the center of an extremely small disturbed area. The relation between the intensity and the area is by no means constant. On the one hand, we may have an earthquake like that of Nicolosi in 1901, destroying houses in a minute epicentral area and yet imperceptible at a distance of more than 4 miles, or one like the Ischian earthquake of 1883, leveling every building within an area of 3 square miles, and yet felt within an area of not more than 1,250 square miles. On the other hand, we may have an earthquake like the Albano earthquake of 1906, not strong enough to damage houses at the epicenter and yet felt over an area of 535 square miles.

c) The sound and tremor, with which tectonic earthquakes usually begin, are either absent from volcanic earthquakes, or else of duration so short as to be almost imperceptible.

d) The duration of the shock in volcanic earthquakes is usually short, being very often less than 5 seconds.

e) The length of the focus is inconsiderable when compared with that of tectonic earthquakes. Even in the strongest of volcanic earthquakes, it rarely exceeds 4 or 5 miles, whereas the average length of the focus in British earthquakes (omitting the weakest) is about 12 or 13 miles. This conclusion is also supported by the brief duration of the shock.

f) Some, but not all, volcanic earthquakes are preceded and followed by a rather large number of accessory shocks. In this they resemble tectonic earthquakes. But the after-shocks of volcanic earthquakes are distinguished by the short period of their action. For instance, the series of after-shocks in the Albano earthquake of 1906 lasted for 3 days, in the Ischian earthquake of 1883, for 7 days, in the Fleri earthquake of 1894, for about 3 weeks, in the Linera earthquake of 1914, for nearly 4 weeks, and in the Fondo Macchia earthquake of 1865, for 5 weeks.

(*g*) The after-shocks of volcanic earthquakes are practically confined to the epicentral area. They point to little, if any, tendency toward any extension of the original focus.

h) In a volcanic system such as that of Etna or the Alban Hills earthquakes occur in many different zones, and seismic activity is subject to frequent and sudden migrations from one zone to another. Nevertheless, in any given zone there is often a certain fixity in the epicenters of successive earthquakes, as in those of Fondo Macchia (Etna) and Casamicciola (Ischia).

The most characteristic of these features is the smallness of the disturbed area considering the intensity of the shock at the epicenter. In Great Britain we have no shocks to be compared in strength with those of Fondo Macchia and Ischia. The strongest of British earthquakes are just capable of causing slight damage to buildings (corresponding to the degree 7 of the Mercalli scale), and the average area disturbed by them is 65,900 square miles. Others of intensity 6, only slightly stronger than the Albano earthquake of 1906, are felt over an average area of 24,500 square miles.

As will be seen from Figure 8, the rapid decline in the intensity of the shock is due to the shallowness of the focus. The curves marked *A* and *B* in Figure 8 represent the intensities of the shock at different distances from the origin, *A* corresponding to a focus $\frac{1}{4}$ of a mile in depth, *B* to one at a depth of 2 miles. The curves are drawn on the assumptions that the intensity of the shock at any point of the surface varies inversely as the square of the distance from the focus, and that the impulses are such that the intensity of the shocks vertically above both foci is the same.

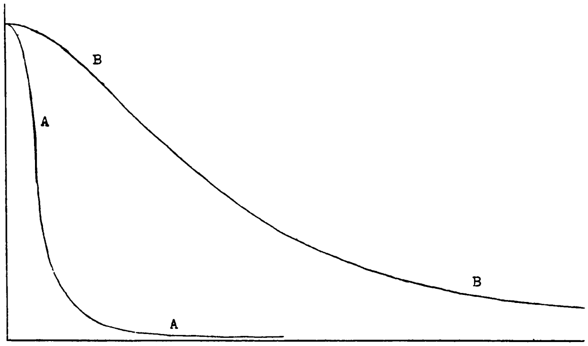

FIG. 8.—Diagram illustrating shallowness of foci in volcanic earthquakes

On these assumptions it follows that the shock that would just be perceptible at a distance of 2 miles from the center for the shallow focus would be perceptible at a distance of 32 miles for the deeper one—that is, the disturbed area of the shock with the deeper focus would be 256 times the disturbed area of the other shock.

It follows, then, that the foci of most volcanic earthquakes are situated at a very slight depth below the surface, and further that the foci vary in depth, the focus of an earthquake like the Nicolosi earthquake of 1901 or the Fondo Macchia earthquake of 1911 being much nearer the surface than that of the Albano earthquake of 1906.

This inference, as to the shallowness of the foci in volcanic earthquakes, is supported by two other lines of evidence. In the

Ischian earthquakes of 1881 and 1883 the depth was estimated, from the inclination of the fissures in walls, to be $\frac{1}{3}$ mile. Again, the duration of the preliminary tremor of an earthquake increases with the distance from the focus, and the practical absence of any such tremor therefore points to the nearness of the focus to the surface.

We may thus conclude: (*a*) that the foci of volcanic earthquakes are situated at a very slight depth below the surface; (*b*) that the foci are usually small and seldom more than 4 or 5 miles in length; (*c*) that the after-shocks, when they occur, originate chiefly within the focus of the principal earthquake; and (*d*), from the discussion of the Etnean and Alban earthquakes, that, while the majority of volcanic earthquakes originate along radial fractures of the mountain, some, and by no means the least important, originate along perimetric fractures.

III. THE ORIGIN OF VOLCANIC EARTHQUAKES

The earthquakes which occur in the neighborhood of active or dormant volcanoes are naturally attributed to the processes which sooner or later tend to result in an eruption. As any sudden displacement of material within the earth's crust may give rise to an earthquake, the processes which have been suggested as possible causes may be grouped under the following heads:

a) The formation of new fractures, or the reopening or extension of old fractures, in the mountain mass, due to the pressure of the column of lava or of gaseous materials in their progress toward the surface.

b) Explosions of any kind, such as those from the sudden generation of steam within the volcano by the access of water to the highly heated rocks below.

c) The sudden injection of fluid rock into fractures or cavities formed in the mass of the volcano.

d) The slipping of the rock surfaces adjoining a fracture due to subterranean movements of the magma.

All of these are possible causes of volcanic earthquakes, and all four processes may be in action during or near the time of an eruption. The question we have now to consider is which cause must be appealed to as offering the best explanation of the various phenomena of volcanic earthquakes.

For a long time the rending of the mountain mass has been regarded as a probable cause of volcanic earthquakes. G. P. Scrope wrote:

> It may very plausibly be suspected that each of the shocks by which the environs of a volcano are so repeatedly agitated, during, and previous to an eruption, is occasioned by the rending of some part of the solid frame-work of the mountain or its supporting strata, by the action of the force—resulting from the pressure in all directions of the liquid which is in communication with that elevated within the volcanic chimney. The prolongation or widening of a fissure previously formed would have the same jarring, or vibratory effect, as the creation of a new one.[1]

Nearly half a century later[2] Scrope repeated this paragraph with hardly any change except in the initial words, and these were altered to "there can be little doubt that," etc. That the fracturing of the mountain mass would be attended with considerable noise and some perceptible vibration cannot be disputed. Whether it is competent to produce earthquakes so strong as those which visit the southeastern flank of Etna or to give rise to the earthquake phenomena described above is less clear and remains, I think, unproved.[3]

Professor Omori ascribes volcanic earthquakes without explosions to the underground expansive force which produces cracks at the depth of a few kilometers; and those with explosions partly to the upward extension of the cracks, and partly, as regards the slow movements, to the outward pushing of the mountain mass consequent to the explosion.[4] If this be the case, it would seem that the earthquakes due to explosions would usually be of slight intensity, for less than 1 per cent of those recorded on the Asama-yama were sensible to the observers on the mountain side. Here, again, we have no doubt a true cause of volcanic earthquakes, but one of unproved competence to produce the destructive shocks that visit the flanks of Etna and Monte Epomeo.

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[1] *Considerations on Volcanos* (1825), p. 155.

[2] *Volcanos* (1872), p. 163.

[3] The explanation has received support from well-known seismologists, among others from G. Mercalli (*Vulcani e Fenomeni Vulcanici in Italia* [1883], pp. 354–55), J. D. Dana (*Characteristics of Volcanoes* [1890], p. 22), F. Omori (*Bull. Imp. Earthquake Inv. Com.*, Vol. VI [1912], pp. 132–33), and A. Riccò (*Boll. Soc. Sis. Ital.*, Vol. XVI [1912], p. 32), but not from H. J. Johnston-Lavis (*Monograph of the Earthquakes of Ischia* [1885], p. 92).

[4] *Bull. Imp. Earthquake Inv. Com.*, Vol. VI (1912), pp. 132–33.

The sudden injection of lava into fissures and cavities would seem to be more effective and was regarded by the late Dr. H. J. Johnston-Lavis as the cause of the Ischian earthquakes. The theory may be held to account for the extreme localization of the earthquakes, for their repetition time after time in the same region, and for the brevity and sudden onset of the shock.[1]

Within the last few years the view has been gradually gaining ground that many of the stronger volcanic earthquakes are in reality tectonic earthquakes precipitated by volcanic action, that they are due not so much to the actual formation of fractures within the mass of the mountain as to slipping along pre-existing fractures. This view has the merit of connecting the earthquakes under extinct volcanoes such as the Alban Hills, with those, from which they do not in reality differ, under active or dormant volcanoes.

Professor G. Platania has shown that the Linera earthquake of May 8, 1914, was connected with a pre-existing fracture of the volcano, and he urges that subterranean movements of the magma have produced powerful tensions in the eastern region of Etna, by means of which the strata have been fractured, or pre-existing fractures have been enlarged, or the strata have slipped along them, and that these are the causes of the earthquakes.[2]

In some of the mining districts of Great Britain local earth-shakes occur which resemble the Etnean earthquakes so closely in their nature, and probably also in their origin, that it may be useful to give a brief description of one of them.

In Figure 9 are shown the isoseismal lines of an earth-shake which occurred at Pendleton (near Manchester) on November 25, 1905. The intensity of the shock was as high as 7 according to the Rossi-Forel scale (or 6 according to the Mercalli scale). The shock was felt over an area of 144 square miles. As the average disturbed area of British earthquakes of the same intensity is 24,500 square miles, it is evident that the earthquake originated at a very slight depth. The mean direction of the longer axes of the isoseismal lines is N.37° W. That of the Irwell Valley fault near the epicenter (represented by the broken line on the map) is N.34° W. It would therefore seem probable that the earth-shake was due to a slip along this well-known fault, and at a depth so small that it may well have occurred within the portion of the crust penetrated by the pit-workings at Pendleton. If this be the case, the fault-slip must have been precipitated, not by the natural and gradual growth of the fault, but by the removal of the rock which, it is known, has been effected right up to the

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[1] *Monograph of the Earthquakes of Ischia* (1885), pp. 89–95.

[2] *Pubbl. dell'Ist. di Geog. Fis. e Vulcan. della R. Univ. di Catania,* No. 5 (1915), p. 41.

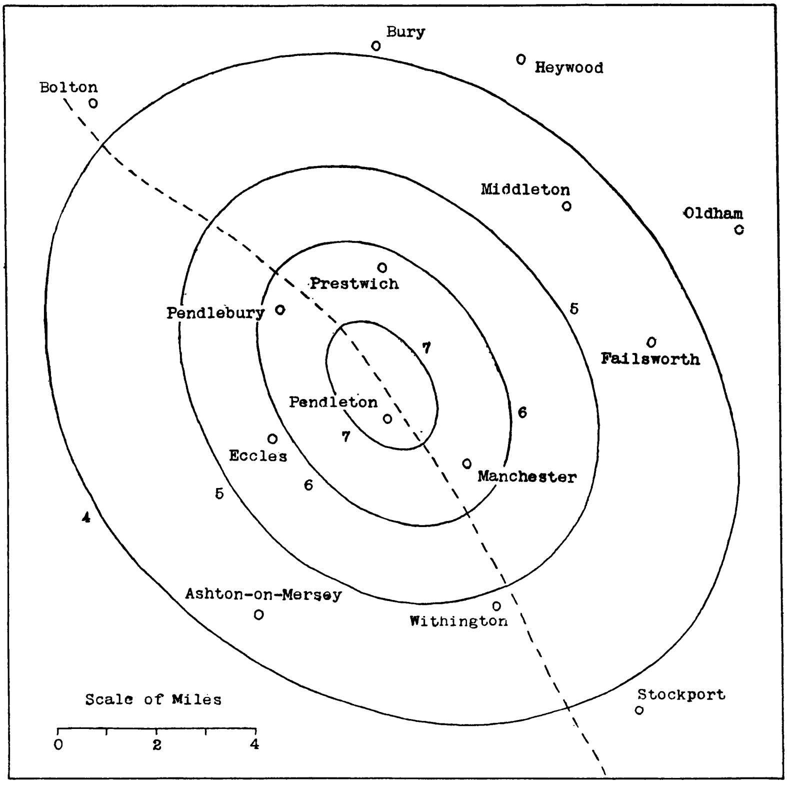

FIG. 9.—Map of Pendleton earth-shake of November 25, 1905

fault, or, possibly, by the pumping of water from the mine.[1] In other words, the Pendleton and other similar earth-shakes are of natural origin in so far as they are due to the growth of faults, but of artificial origin in that the slips are precipitated by mining operations.

An active volcano is coursed by many fractures, the majority of which are radial, but a few perimetric. If the rock mass or masses were in some way to be deprived of support, one mass would slide against the other, and the friction of the grating surfaces would give rise to an earthquake, not to be distinguished, except by its scale, from a true tectonic earthquake. In what way or ways could the rock mass be deprived of its support? Professor Platania suggests by underground movements of the magma,[2] and this might evidently be the case beneath active, and possibly beneath dormant, volcanoes. In all kinds of volcanoes, and especially in extinct volcanoes, another cause may be in operation, though acting much more slowly and giving rise therefore to infrequent shocks like those of Ischia. This is the gradual cooling of lava or heated rock beneath the fractured mass. And it should be noticed that the intensity of the resulting shock would not depend so much on the distance to which the support is withdrawn as on the area of the focus and on the weight of the rock displaced.

This theory, it will be seen, accounts for all the known phenomena of volcanic earthquakes—for their close connection in space and time with many eruptions, the shallowness of their foci and the great intensity of the shock within a limited area, the small size of the foci and the brief duration of the shocks, the occurrence of series of fore-shocks and after-shocks limited in duration and in space chiefly to the original focus, and, lastly, for the occurrence of volcanic earthquakes beneath dormant and extinct, as well as beneath active, volcanoes.

If this is the correct explanation of the cause of the more important volcanic earthquakes, it follows that such earthquakes are of tectonic origin in so far as they are due to the growth of faults, but of volcanic origin in that the slips are precipitated by present or past volcanic operations.

[1] *Geol. Mag.*, Vol. III (1906), pp. 171–76.

[2] *Pubbl. dell'Ist. di Geog. Fis. e Vulcan. della R. Univ. di Catania*, No. 5 (1915), pp. 1–2, 41.